DOWNSCALED CLIMATE AND STREAMFLOW STUDY OF THE SOUTHWESTERN UNITED STATES[1]

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ABSTRACT: Downscaling coarse resolution climate data to scales that are useful for impact assessment studies is receiving increased attention. Basin-scale hydrologic processes and other local climate impacts related to water resources such as reservoir management, crop and forest productivity, and ecosystem response require climate information at scales that are much finer than current and future GCM resolutions. The Regional Climate System Model (RCSM) is a dynamic downscaling system that has been used since 1994 for short-term precipitation and streamflow predictions and seasonal hindcast analysis with good skill. During the 1997-1998 winter, experimental seasonal forecasts were made in collaboration with the NOAA Climate Prediction Center and UCLA with promising results. Preliminary studies of a control and $2xCO_2$ perturbation for the southwestern U.S. have been performed.
(KEY TERMS: meteorology/climatology; modeling/statistics/ surface water hydrology; water management; water resources planning.)

INTRODUCTION

The complexity of dynamic and physical processes that determines the hydroclimate of the western U.S. requires a reliable downscaling system. Downscaling by nested limited area models retain large-scale forcing, yet captures local features such as orographic effects. The RCSM (http://esd.lbl.gov/RCSM) has been successfully used in a variety of downscaling studies for the western U.S. including short-term weather and streamflow predictions (Miller and Kim, 1996; Miller *et al.,* 1997) and seasonal-scale climate and streamflow hindcasts (Kim, 1997; Kim *et al.,* 1998). A physically based downscaled seasonal prediction experiment took place during the 1997-1998 winter season with promising results. In 1999, the Regional Climate Center initiated long-term multi-year climate studies of a climate hindcast (control) and projected $2xCO_2$ climate scenario for impact assessments of streamflow, and water resources in the western U.S. This long-term climate study is focused on the Sacramento-San Joaquin River system and the Colorado River system and is in collaboration with the NOAA/NWS California-Nevada River Forecast Center and the USGS at Denver.

The following sections describe the Regional Climate System Model, short-term weather and streamflow prediction experiments, seasonal hydroclimate hindcast studies, the 1997-1998 seasonal forecast experiment, and preliminary results from a downscaled regional climate and $2xCO_2$ impacts study.

REGIONAL CLIMATE SYSTEM MODEL (RCSM) DESCRIPTION

The Regional Climate System Model (RCSM) has been under development since 1991. The RCSM is composed of a pre-processor, process models and a post-processor (Figure 1). The pre-processor imports large-scale data and prepares input data for the process models. The process models simulate regional- and basin-scale features of the atmosphere, land-surface, and streamflow from the large scale data using the Mesoscale Atmospheric Simulation (MAS) model, Soil-Plant-Snow (SPS) model, and a suite of hydrologic models that include a semi-distributed version of TOPMODEL and spatially lumped Sacramento

[1]Paper No. 99060 of the *Journal of the American Water Resources Association.* **Discussions are open until August 1, 2000.**
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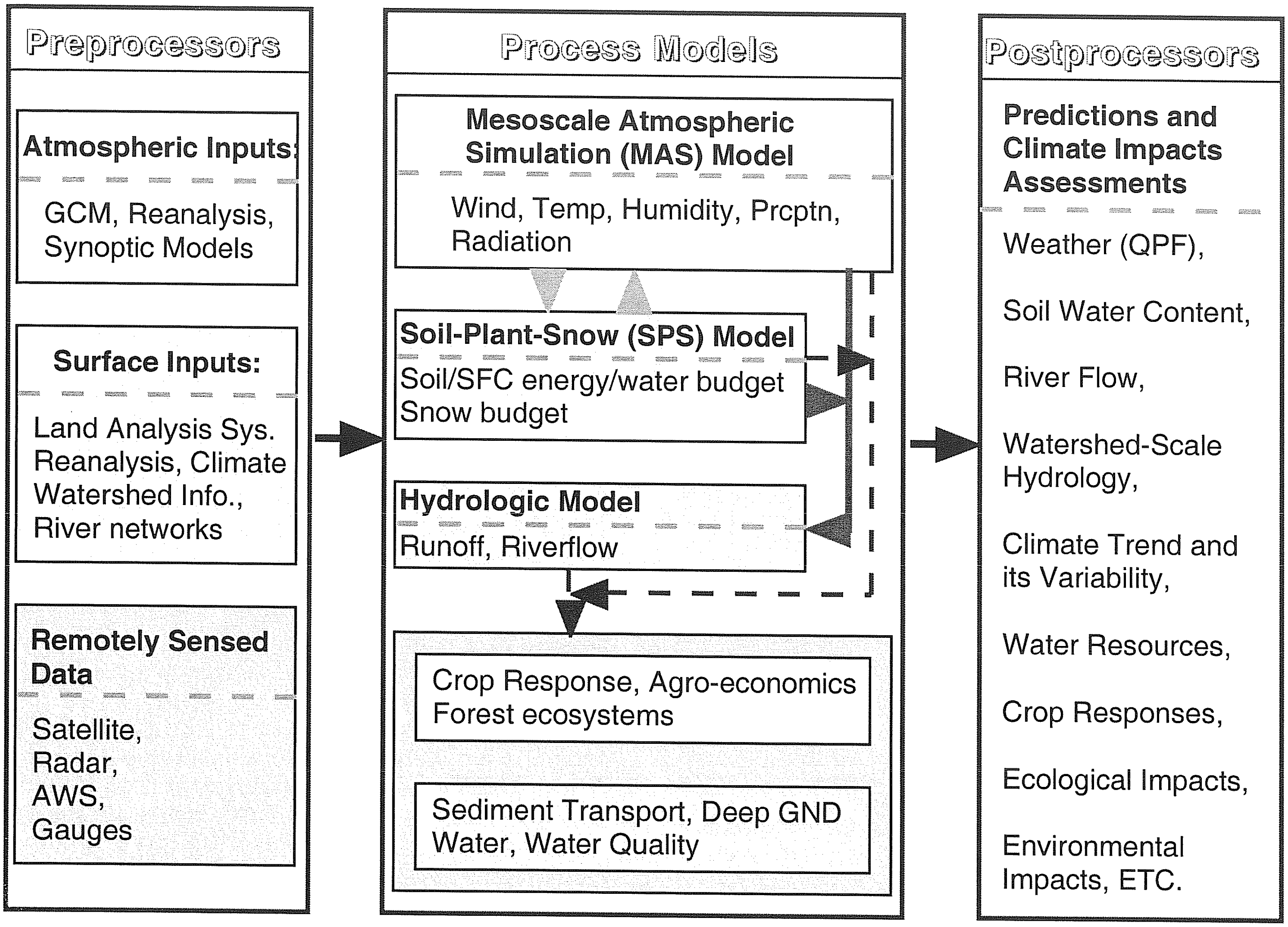

Figure 1. A Schematic Illustration of the Regional Climate System Model.

model. The post-processor includes analyses of the RCSM output and impact assessment models.

The process and impact-assessment models of the RCSM include interactions among atmospheric, land-surface, and subsurface processes. The MAS model (Kim and Soong, 1996; Soong and Kim, 1996) is a physically based hydrostatic limited-area model. It includes a third-order accurate advection scheme (Takacs, 1985), multi-layer solar and terrestrial radiation schemes (Harshvardhan *et al.,* 1987), and a bulk cloud microphysics scheme (Cho *et al.,* 1988). The Soil-Plant-Snow model (Kim and Ek, 1995) includes heat and moisture transfer within a multi-layer soil. It includes the effects of vegetation on the surface energy and water budgets to compute evapotranspiration, and a single layer snow model. TOPMODEL is a statistical dynamical hydrologic-streamflow model (Beven and Kirkby, 1979) that uses surface topography as a characteristic index for surface and baseflow water transport. TOPMODEL simulates spatial distributions of soil moisture using similarity of the topographic index value and transmissivity, as well as vegetation and soil characterizations. It has been advanced to include a generalized power function for the subsurface transmissivity profile (Ambroise *et al.,* 1996; Duan and Miller, 1997) and a deep water flux term. RCSM also includes the modified version of the physically based spatially lumped Sacramento Model (Georgakakos, 1986a, 1986b). Further details of these models are provided in the literature.

In addition to the models above, the RCSM includes impact assessment models for water resources, forest productivity and agro-ecosystem response. We are currently implementing additional assessment components including a water quality monitoring system, landslide model, sediment transport model, and a rural economic response model for the California Central valley, as part of our detailed southwestern U.S. end-to-end system for better understanding climate variability and change on water resources and related sectors.

A SHORT-TERM NUMERICAL WEATHER AND STREAMFLOW PREDICTION EXPERIMENT

A short-term numerical prediction experiment was designed to provide fine-scale weather and streamflow forecasts. Among the information from this operational forecast experiment are basin-scale quantitative precipitation and streamflow forecasts that are important for managing water resources and flood forecasting. The forecast period presented in this study is 48 hours, with daily updates, using the NCEP gridded forecast products from the 80 km resolution Eta model as input. At the beginning of each forecast period the RCSM was initialized by interpolating the NCEP data. The time-dependent lateral boundary conditions were obtained from the NCEP forecast data. Streamflow was initialized by a specified saturation deficit storage (300 mm) and is updated every 48-hour by the previous 24 hour simulated value. Details of this were presented in Miller and Kim (1996).

This regional prediction application began experimental operational forecasts in 1994, and had an early success during the January 1995 storms in California. Between January 7 and January 11, three strong consecutive storms hit northern California with daily precipitation exceeding 250 mm at several parts of the northern California coastal range and caused severe flooding along the Russian River and the Napa River. The RCSM has accurately predicted the amount of rainfall and river discharge from the Hopland basin, the headwater of the Russian River, during this period (Figure 2a). This 1995 precipitation-streamflow prediction was among the first efforts to couple the atmospheric and hydrologic models for downscaled global-to-mesoscale-to-basin-scale predictions. Additionally, heavy precipitation along the northern Coastal Range, the western slope of the Sierra Nevada, and the southern California Coast near Santa Barbara was also well predicted. Using the NCEP Aviation forecast at 1° x 1° resolution, the RCSM has successfully predicted the magnitude and timing of the January 1997 flooding at the Russian River basin 48 hours in advance (Figure 2b). This

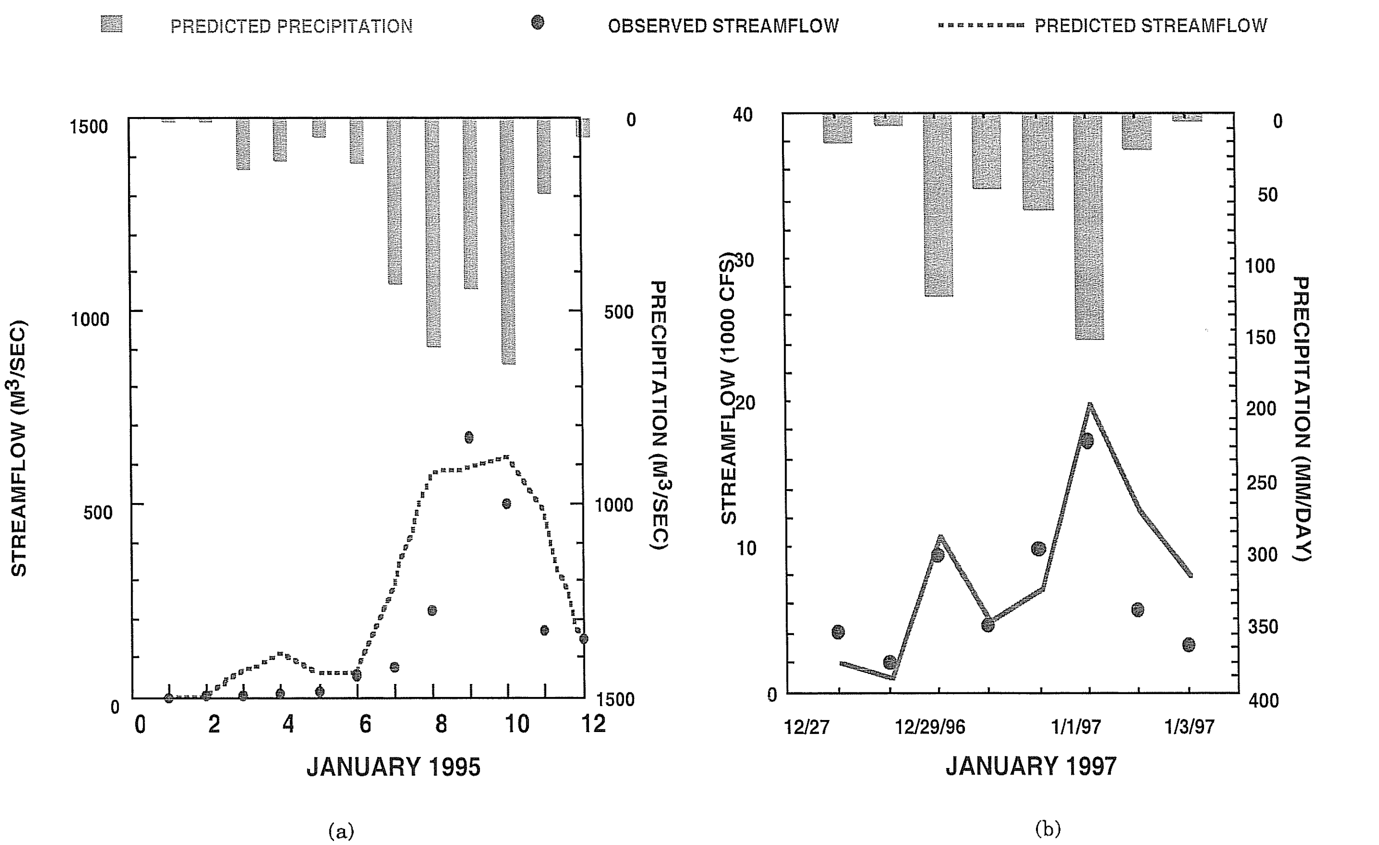

Figure 2. RCSM-Predicted Precipitation and Streamflow at the Hopland Basin: (a) January 1995 Flood, and (b) January 1997 Flood.

short-term experimental weather and streamflow forecast effort has since been expanded to a large set of important California watersheds in collaboration with the California-Nevada River Forecast Center.

SEASONAL HYDROCLIMATE HINDCAST STUDIES

The main goal of this seasonal hindcast experiment is to obtain hydroclimate information for the western U.S. at the end of the wet season. This information complements observations, such as rain and snow measurements, to assess water resources availability during the dry summer season, and to forecast the potential for spring and early summer floods. The hindcast result is also used to evaluate model performance against available observations. The first complete diagnostic simulation was performed for a 20 km-resolution western U.S. domain for the period of November 1994-May 1995. The RCSM has well simulated the temporal and spatial variation of precipitation within California during this season. Figure 3 presents the simulated and observed daily precipitation in California. The RCSM has closely reproduced the occurrence and amount of daily precipitation. Figure 4 compares the observed and simulated monthly precipitation against the California Data Exchange Center rain gauge stations within California. The correlation between the observed and simulated precipitation was better than 0.7 for the entire period. The coupled system has also accurately simulated streamflow at the Hopland basin during this season (Figure 5). The coupled streamflow hindcast has accurately simulated the high flow events of January and March 1995. More details of this 1994-1995 hindcast study were presented in Kim (1997) and Kim *et al.* (1998). This hindcast result indicates the ability of a coupled atmosphere-streamflow simulation system to capture both the timing and magnitude of observed streamflow for a 650 km^2 sub-basin.

During the 1997-1998 season, we experimented with two regional domains, the earlier 20 km resolution southwestern U.S. domain and a new 36 km resolution western U.S. domain. The coarse resolution domain was introduced in preparation for a nested modeling system where a 12 km resolution subdomain for the southwestern U.S. will be nested to capture more detailed orographic effects along the

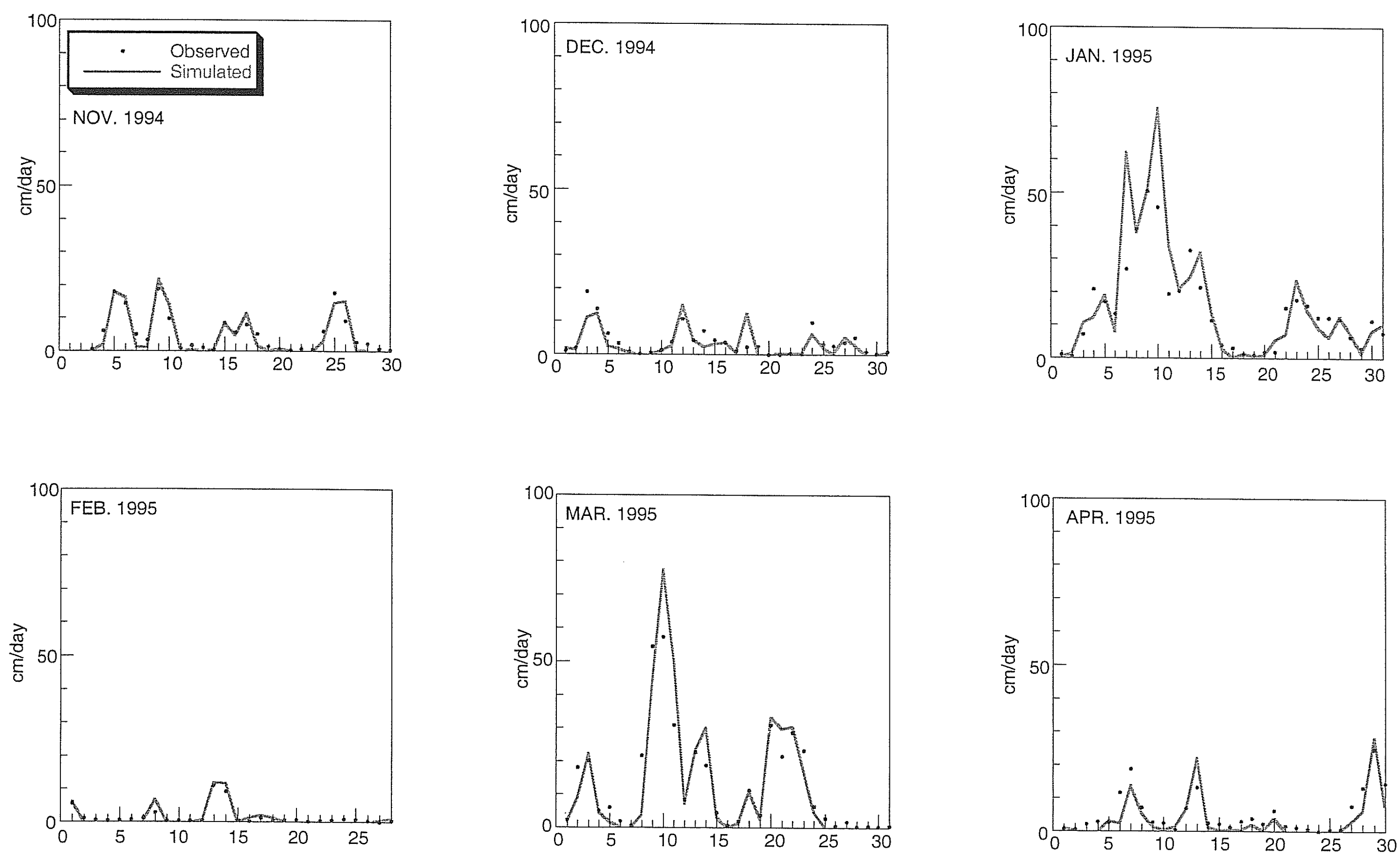

Figure 3. A Comparison of the Simulated and Observed Daily Precipitation in California for November 1994-April 1995.

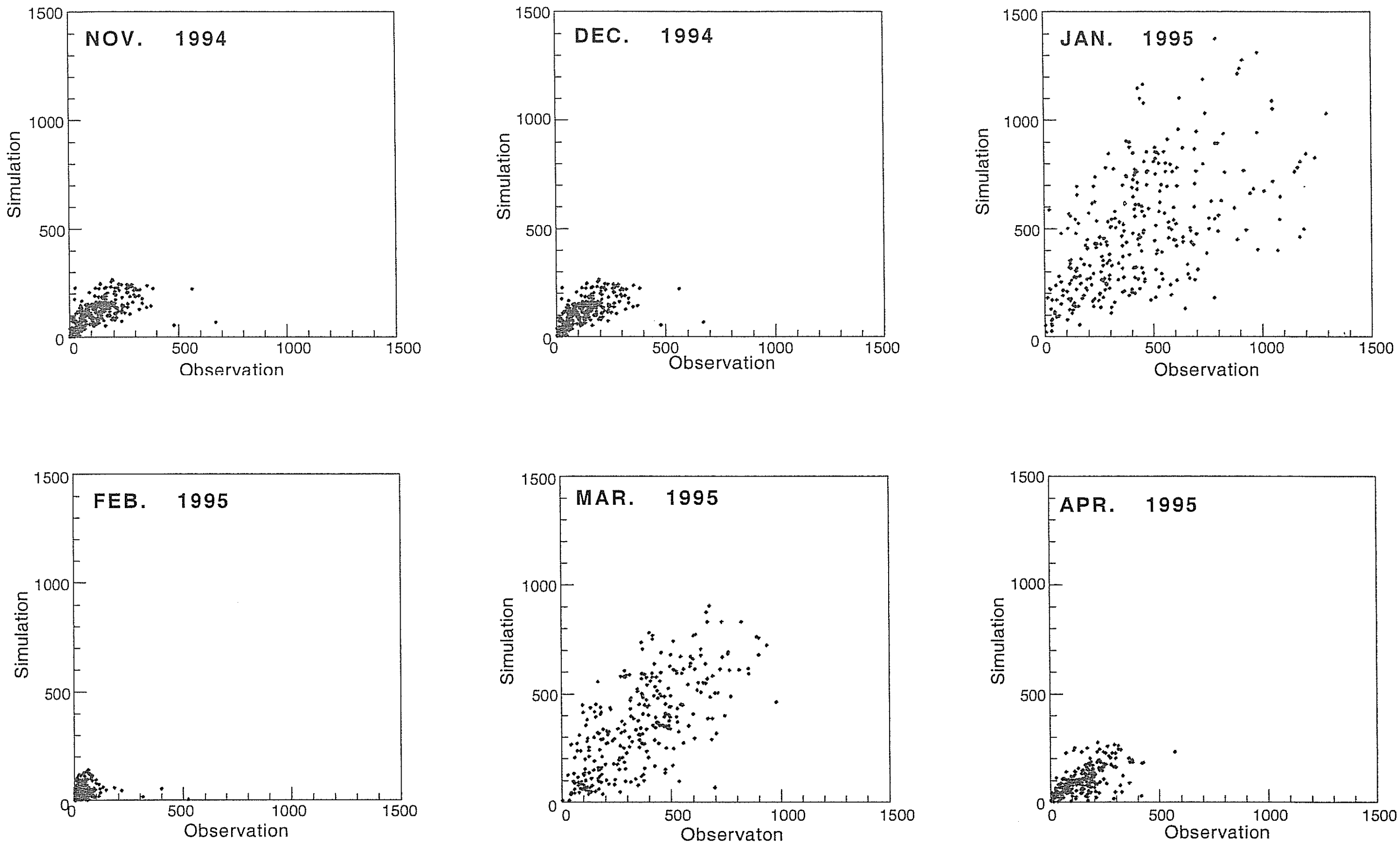

Figure 4. A Comparison of the Simulated and Observed Monthly Precipitation for California for November 1994-April 1995.

coastal regions. Both domains again well simulated the features of precipitation within the western U.S. Figure 6 compares basin-averaged observed and simulated monthly precipitation at six California sub-regions; northern California coastal basins, central California coastal basins, southern California coastal basins, northern central valley basins, northern Sierra Nevada basins, and southern Sierra Nevada basins. The observed precipitation is based on daily precipitation from 188 rain gauge stations in California and the simulated precipitation is basin averaged from the 36 km resolution simulation. Overall, there is good agreement between basin-average observed and simulated precipitation. Detailed analysis of the results indicated that the coarse-resolution simulation did not fully capture the precipitation features along the Southern California Coastal Range. This expected shortcoming due to the coarser resolution will improve with the planned nesting of a much finer resolution domain.

The simulated streamflow, as forced by the RCSM-simulated precipitation, at the Hopland basin for December 1997-February 1998 (DJF) agrees well with

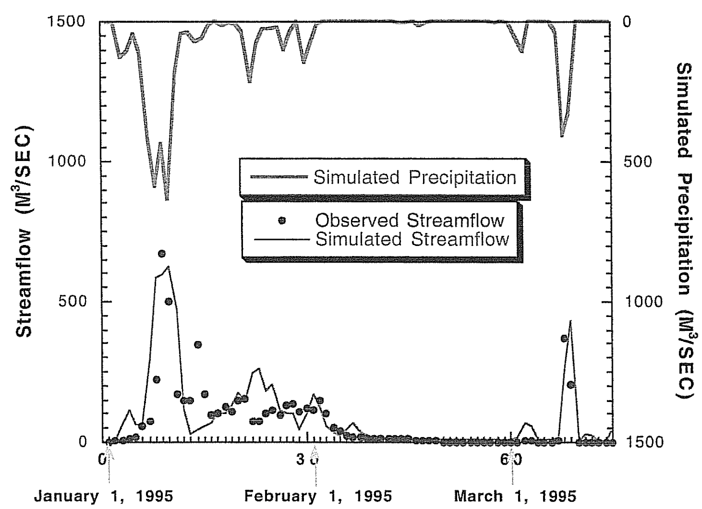

Figure 5. Observed and Simulated Streamflow at the Hopland Gauge Station Along the Russian River, Northern California, for January 1-March 31, 1995.

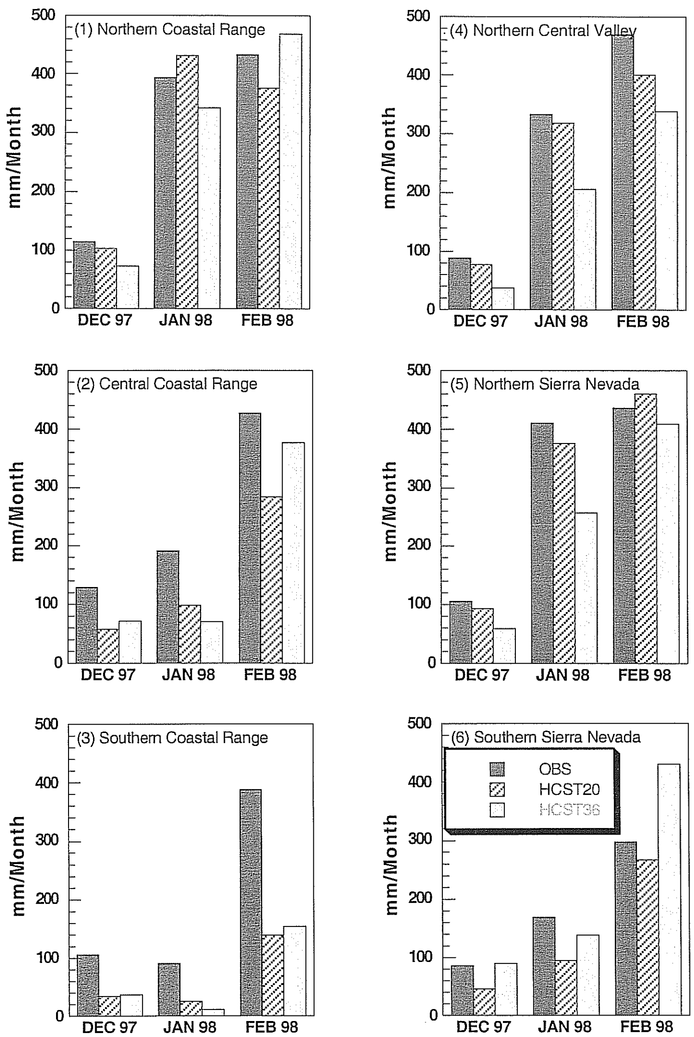

Figure 6. Observed and Simulated Precipitation at Six California Sub-Regions.

observed streamflow (Figure 7). Both TOPMODEL and the Sacramento model showed similar performance at this basin. Initially, TOPMODEL over predicted the amount of baseflow compared to the Sacramento model. TOPMODEL and the Sacramento model both captured the high flows during the January and February 1998 storms. TOPMODEL has captured streamflow recession during the late February to early March period better than the Sacramento Model. Figure 8 compares the frequency distribution of streamflow volume from the observations at the Hopland gauge station to TOPMODEL and the Sacramento model. Low flow was over predicted both by TOPMODEL and the Sacramento model. High flow is well simulated by TOPMODEL, but the Sacramento model missed several high flow events.

SEASONAL HYDROCLIMATE FORECAST FOR THE WESTERN U.S.

The seasonal climate prediction experiment for the western U.S. was a collaborative effort between the Berkeley Lab Regional Climate Center, UCLA Atmospheric Sciences Department, NOAA Climate Prediction Center (NOAA-CPC), and Scripps Institution of Oceanography. This downscaled nested-modeling approach for a seasonal prediction took place prior to the extreme El Niño winter of 1997-1998. For regional forecasts, RCSM utilized the global forecast data from UCLA for time-dependent forcing at the lateral boundaries. The SST forecast data to drive the UCLA-GCM was generated at the NOAA Climate Prediction Center. The seasonal forecast experiment was performed using the same 36 km resolution domain that

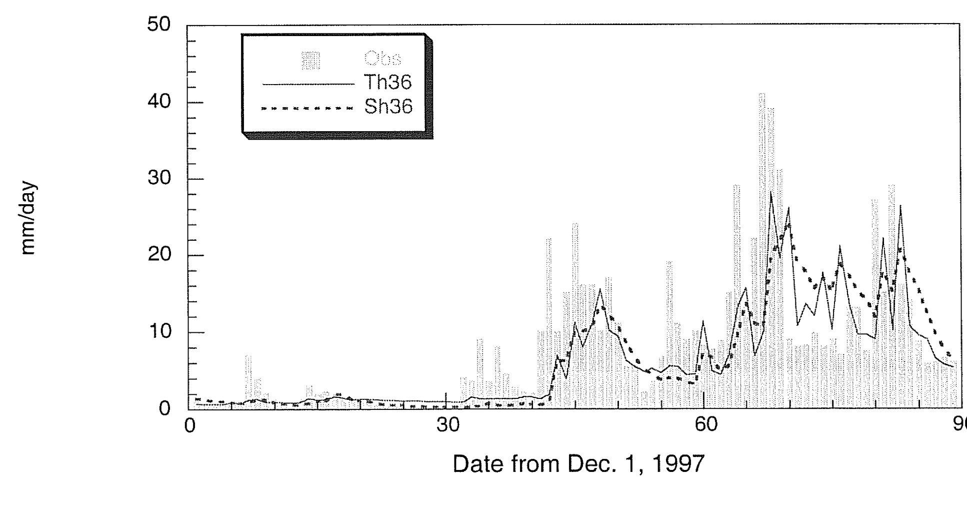

Figure 7. Observed and RCSM-Simulated Streamflow at the Hopland Basin for December 1997-February 1998 Using TOPMODEL and the Sacramento Model.

was used for the 1997-1998 hindcast study. Figures 9a and 9b shows that the predicted DJF season-total precipitation has well captured important precipitation features, such as orographic effects of precipitation on the western U.S. (e.g., the Coastal Range, the Sierra Nevada, and the Cascade Mountains) which are not resolved at the GCM scale. Examination of the season-total precipitation in the six California subregions also suggests that the spatial distribution of DJF-total precipitation also compares well with observation and the hindcast simulation (Figure 10).

Analysis of the streamflow forecast indicates that the DJF total flow is about the same as the amount from the hindcast (Figure 11). However, the forecast flow rate has shifted to the low flow range due to the atmospheric results reported above. The forecast result captured one high flow event (35 mm/day) that the hindcast did not, perhaps by coincidence. The time series (not shown) missed the high flow during February. There is a need to further refine this new approach to extend daily forecasts into the seasonal time scale.

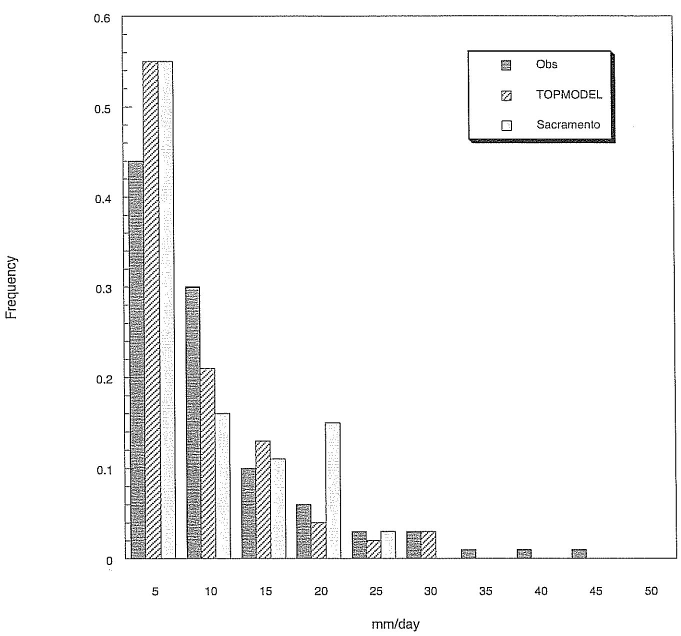

Figure 8. A Comparison of the Frequency Distribution of the Observed and Simulated Streamflow at the Hopland Gauge Station Using TOPMODEL and the Sacramento Model.

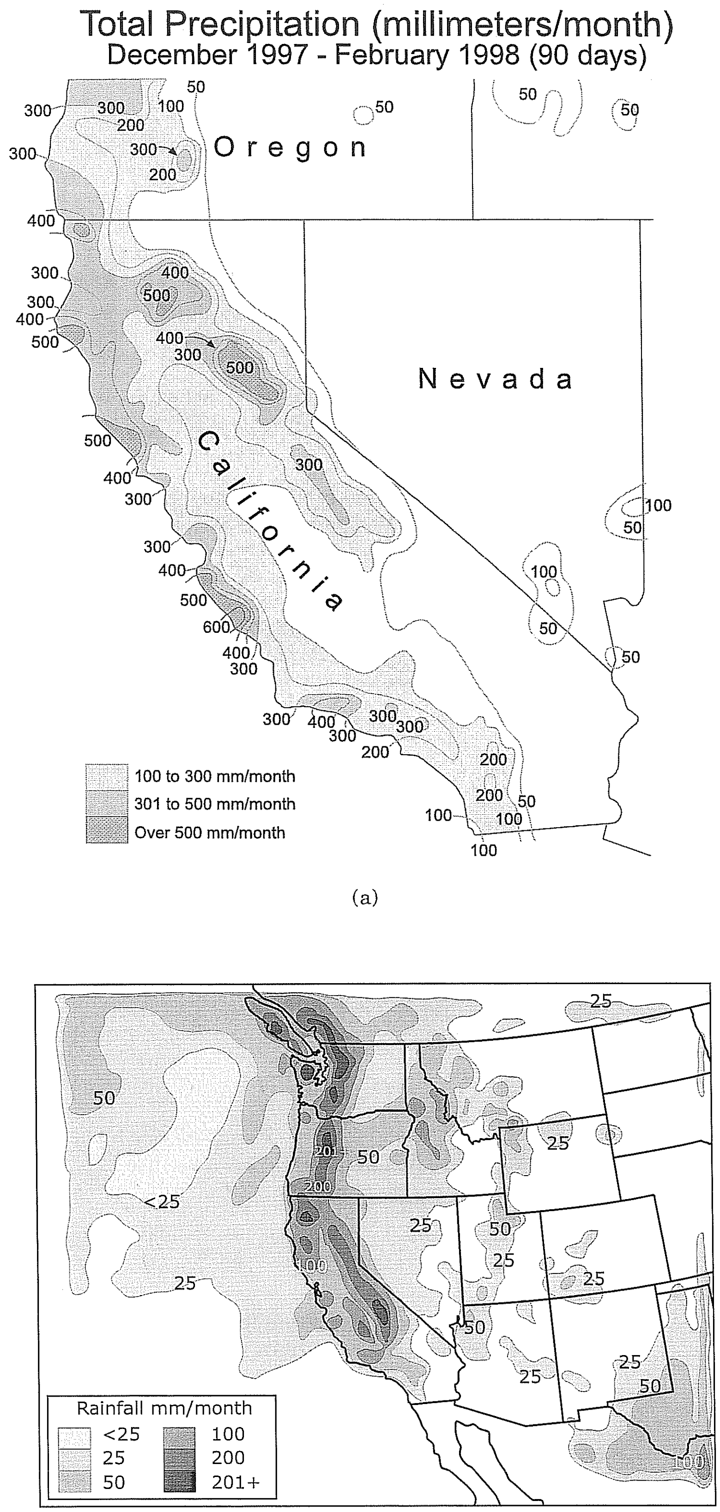

Figure 9. DJF Season Total Precipitation (a) Observed and (b) Predicted.

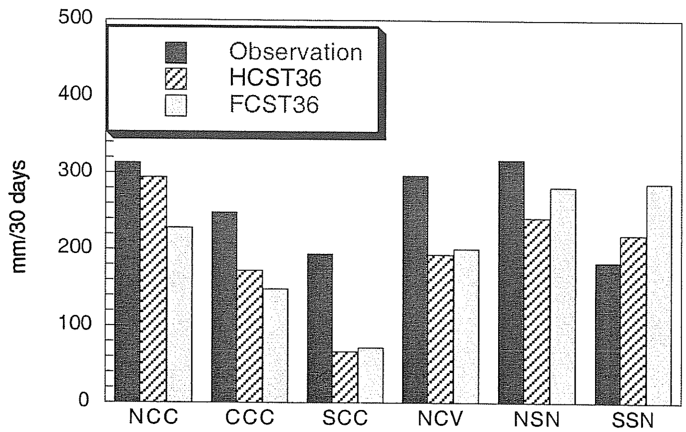

Figure 10. A Comparison of Observed, Hindcast, (HCST36), and Predicted (FCST36) Precipitation in Six California Sub-Regions: North Coastal (NCC), Central Coastal (CCC), South Coastal (SCC), North Central Valley (NCV), North Sierra Nevada (NSN), and South Sierra Nevada (SSN).

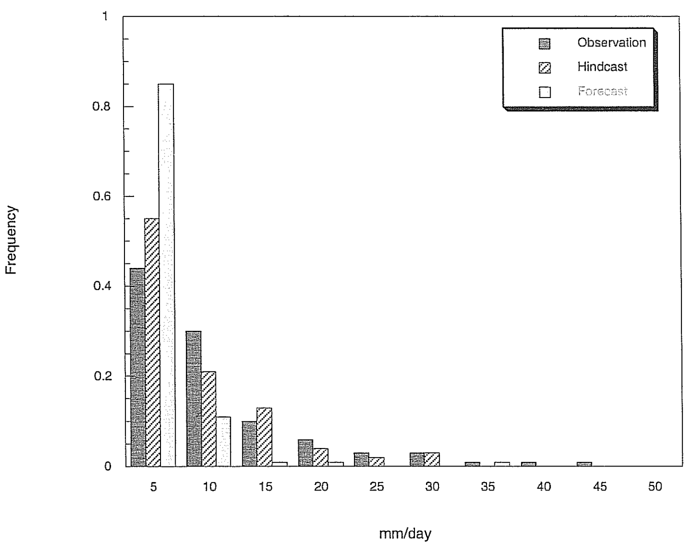

Figure 11. Observed and Simulated Hindcast and Forecast Streamflow for the 1997-1998 DJF.

DOWNSCALED WESTERN U.S. CLIMATE HINDCAST AND 2xCO_2 STUDY

As part of the U.S. National Assessment, the Regional Climate Center has started a series of studies to assess the impacts of increased atmospheric greenhouse gas concentration on the regional hydroclimate, water resources, agriculture, and ecosystems. This climate study includes an examination of a variety of methods to impose GCM-generated scenarios for downscaling. For example, the most direct method to obtain the GCM-projected climate sensitivity at the regional scale is to downscale each member of a GCM-generated ensemble and compute the difference between the downscaled control simulations and sensitivity simulations. This direct method is computationally very expensive, as each GCM ensemble simulation includes 10 or more individual scenarios. We are working to find the most feasible approach for simulating regional-scale climate sensitivity without the massive simulations required by the direct downscaling method.

One alternative method we are examining takes a simplified approach, where only the climate sensitivity generated by GCM ensemble simulations is imposed on the present-day climate record. We call this method the Sensitivity Imposition Method or SIM for brevity. In the SIM approach, we select the climate record that represents the current climate as a control data. The most reliable data sets that represent the control climate are the global reanalysis data from the NCEP and the ECMWF. These data sets consist of sub-daily global atmospheric states for several decades, a period long enough to capture many important features of inter-annual variability and a few inter-decadal variability, and are considered the most accurate archive. Once a control data set is selected, a sensitivity data set is generated by adding (imposing) the climate sensitivity generated by GCMs to the control data set. The next step is to run the RCSM for the two large-scale data sets and compute the RCSM-generated regional scale climate sensitivity. In addition to reduced computational requirements, this method can partially eliminate uncertainties in the climate variability generated by GCM control simulations. The most critical shortcoming of the SIM is that GCM-generated temporal variability, especially at the scales of individual storms, are not well accounted for. Our immediate work plan includes examining the SIM approach against the direct downscaling method.

In this preliminary study, we selected the NCEP reanalysis data as the control data set to represent the current climate. To generate a sensitivity data set, the monthly-mean temperature and water vapor mixing ratio differences between the control and 2xCO2 ensemble simulations of the Hadley Centre's HADCM2 (Jones *et al.* 1997) were used. In this experiment, we examined the effects of the atmospheric temperature and moisture on the regional hydroclimate. Note that this preliminary experimental arrangement does not account for the variation of the storm tracks due to 2xCO_2 forcing. Generating sensitivity data sets that can account for more complete GCM-generated variability is an ongoing research subject.

Figure 12a illustrates the downscaled mean-annual precipitation for 1981-1984 from the control run. This four-year control run has well simulated climatological features of precipitation in the western U.S. as seen from a 30-year precipitation analysis from the Western Regional Climate Center at the Desert Research Institute (Figure 12b). The heavy precipitation along the Coastal Range, the Cascades, and the Sierra Nevada is well simulated in the control run. Locations of precipitation maxima at the interior of the western U.S., (central Utah, western Colorado, central Arizona, northwestern Wyoming, and central Idaho) were also well simulated. Underestimation of precipitation at the southern California Coastal Range, Oregon coast, and eastern Montana indicates that the spatial resolution of 36 km x 36 km is not sufficient to represent significant orographic features in those regions as discussed by Kim *et al.* (1997). Figure 13 compares the observed and simulated monthly precipitation at two California watersheds, the Hopland basin at the northern Coastal Range and the Feather River basin at the northern Sierra Nevada using the simulated precipitation. The control run has well simulated the basin-scale precipitation at these two basins except late 1981 when the RCSM has somewhat underestimated precipitation at both basins. A more quantitative evaluation of this climate hindcast is underway.

Figure 14 presents the sensitivity of the mean seasonal water vapor mixing ratio from the HADCM2 (Doherty and Mearns, 1999). This ensemble scenario suggests that atmospheric water vapor will increase throughout the western U.S., especially during summer and fall. The amount of projected increase of water vapor exceeds 4 g/kg over a significant portion of the western U.S. including southeastern California, Arizona, New Mexico, and Colorado. Accuracy of this GCM projection can not be evaluated at this time.

The mean-annual precipitation difference between the control simulation and 2xCO_2 projection is shown in Figure 15. As a direct response to increased atmospheric water vapor, the downscaled simulation has predicted that precipitation at the interior part of the western U.S. will increase significantly. The area where the largest increase of precipitation was predicted coincides with the area where the atmospheric moisture was predicted to increase most by the global model. This result shows that the RCSM's

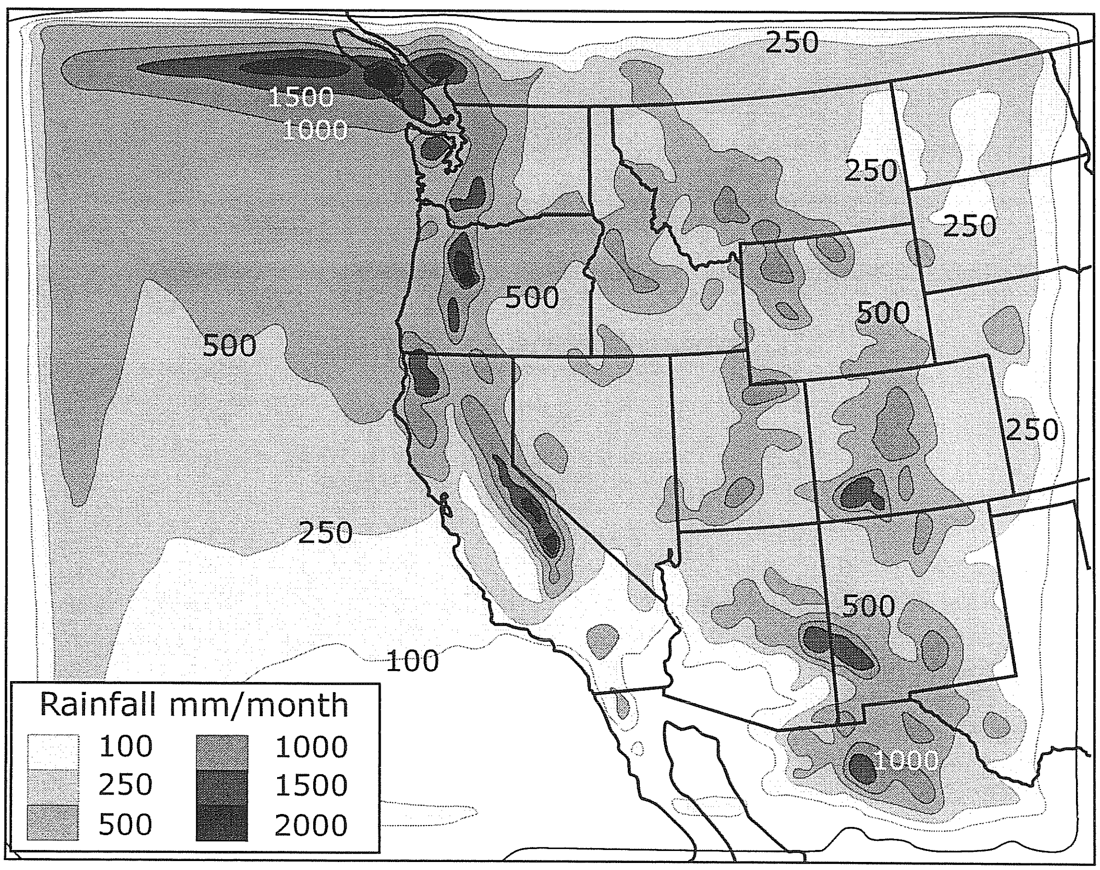

Figure 12a. The Mean-Annual Precipitation for 1981-1984 From the Control Simulation.

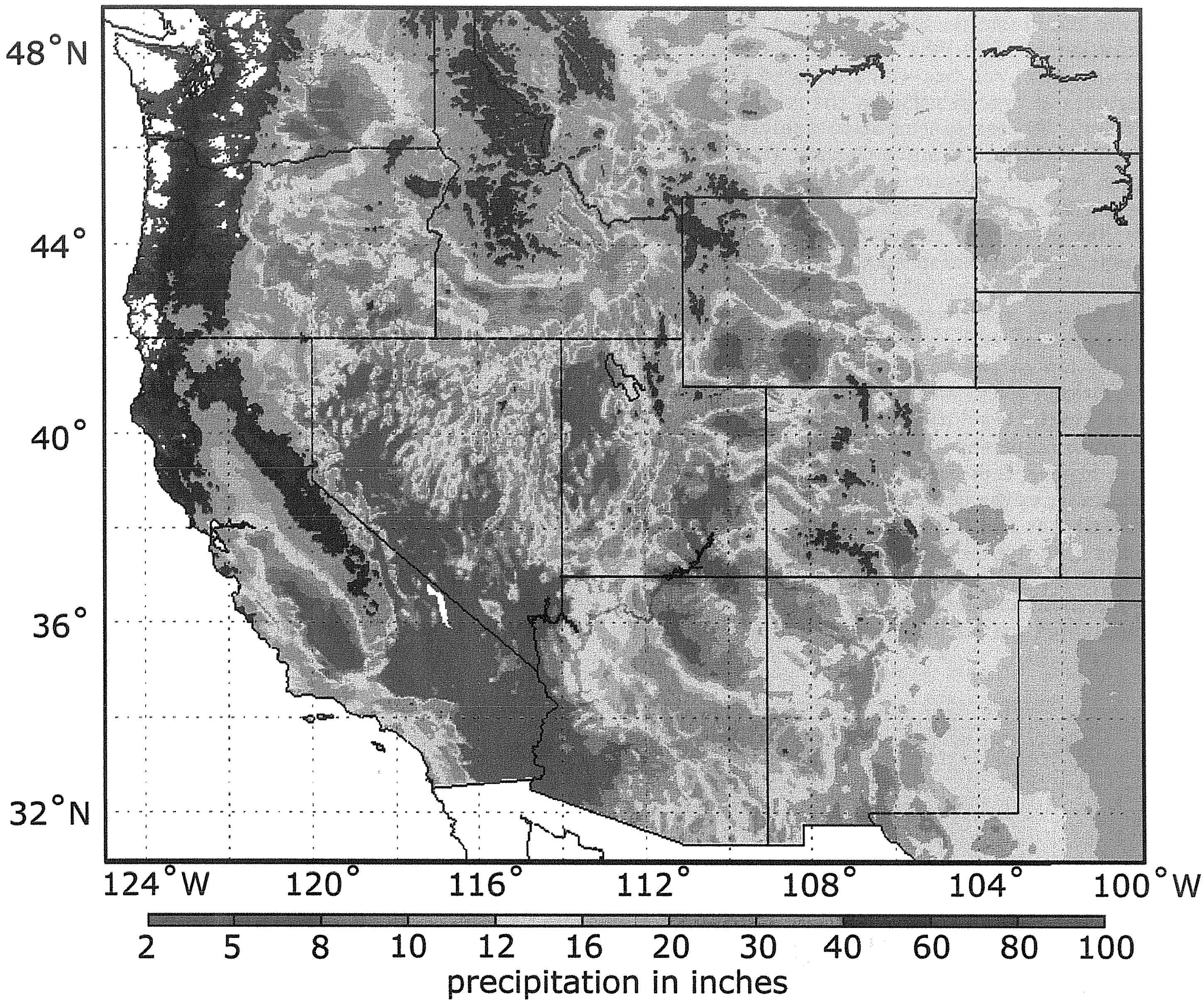

Figure 12b. A 30-Year Precipitation Climatology From the Western Regional Climate Center at the Desert Research Institute.

response to the variation of large-scale forcing is correct, at least qualitatively. Sub-daily global data produced by the HADCM2 simulation was not available to us and not used for a direct downscaling study. Further evaluation and development of the SIM approach will be carried out using GCM scenarios where sub-daily archived data are available.

For this preliminary sensitivity experiment, we used the RCSM version of TOPMODEL to simulate the sensitivity of streamflow to the increased CO_2-based HADCM2 simulation. As described above, the RCSM version of TOPMODEL is calibrated for both daily and six-hour timesteps at the Hopland subbasin of the Russian River. Using the 36 km daily time series for the control and $2xCO_2$ simulations, we produced a sensitivity response of streamflow. Figure 16 indicates the resulting response of mean-monthly streamflow as forced by the 1981-1984 control and $2xCO_2$ daily time series. This result implies that there may be a shift in the timing of peak streamflow from March to February.

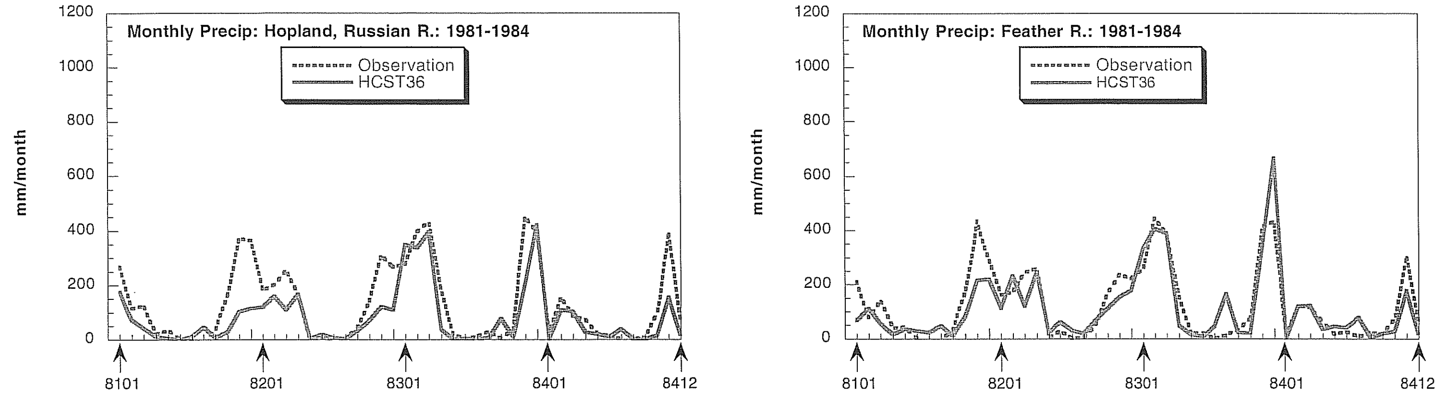

Figure 13. Observed and Simulated Monthly Precipitation at Two California Watersheds: The Hopland Basin in the North Coastal Range and the Feather River Basin in the Northern Sierra Nevada.

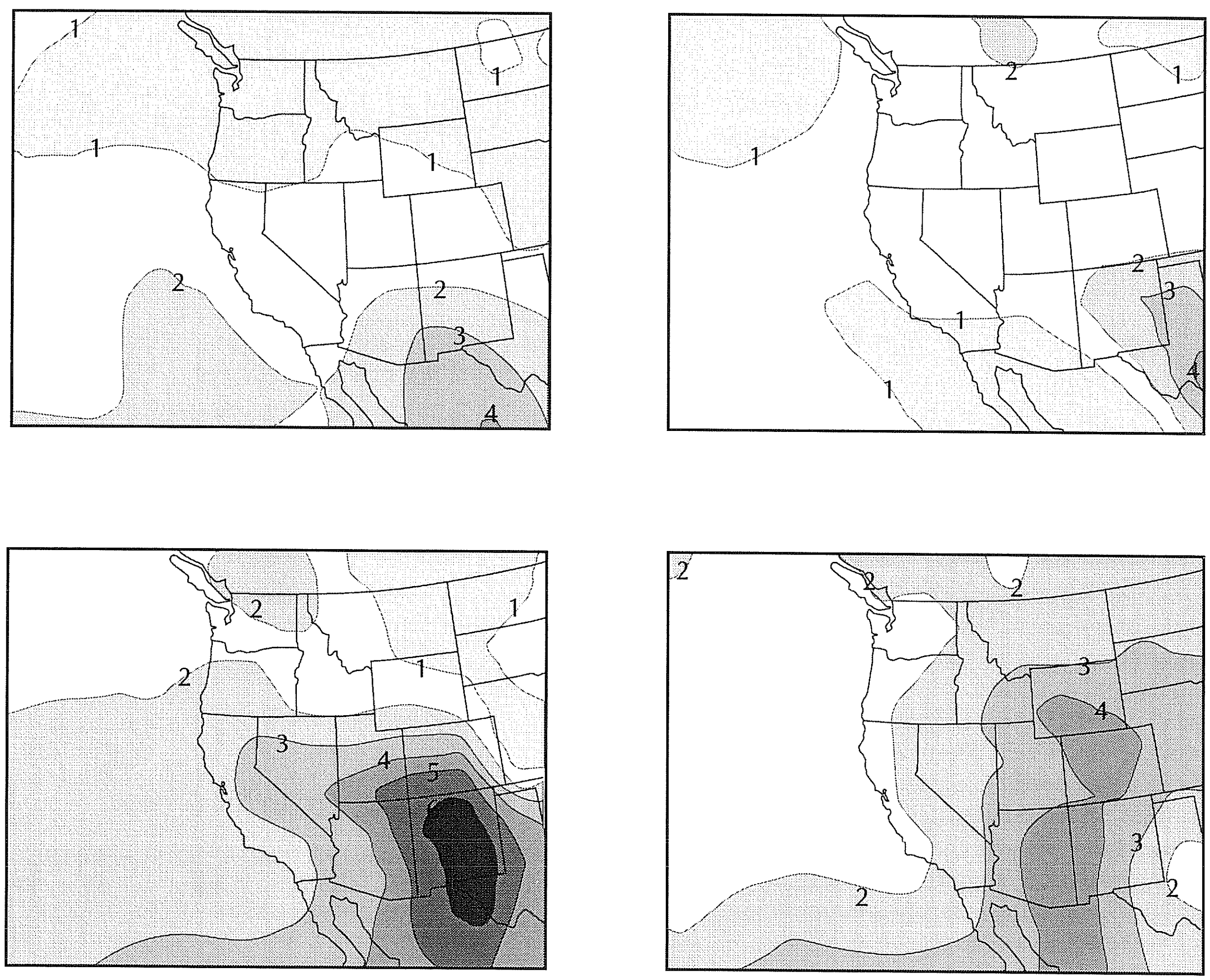

Figure 14. Sensitivity of the Mean Seasonal Water Vapor Mixing Ratio Due to $2xCO_2$ From the HadCM2 Simulations.

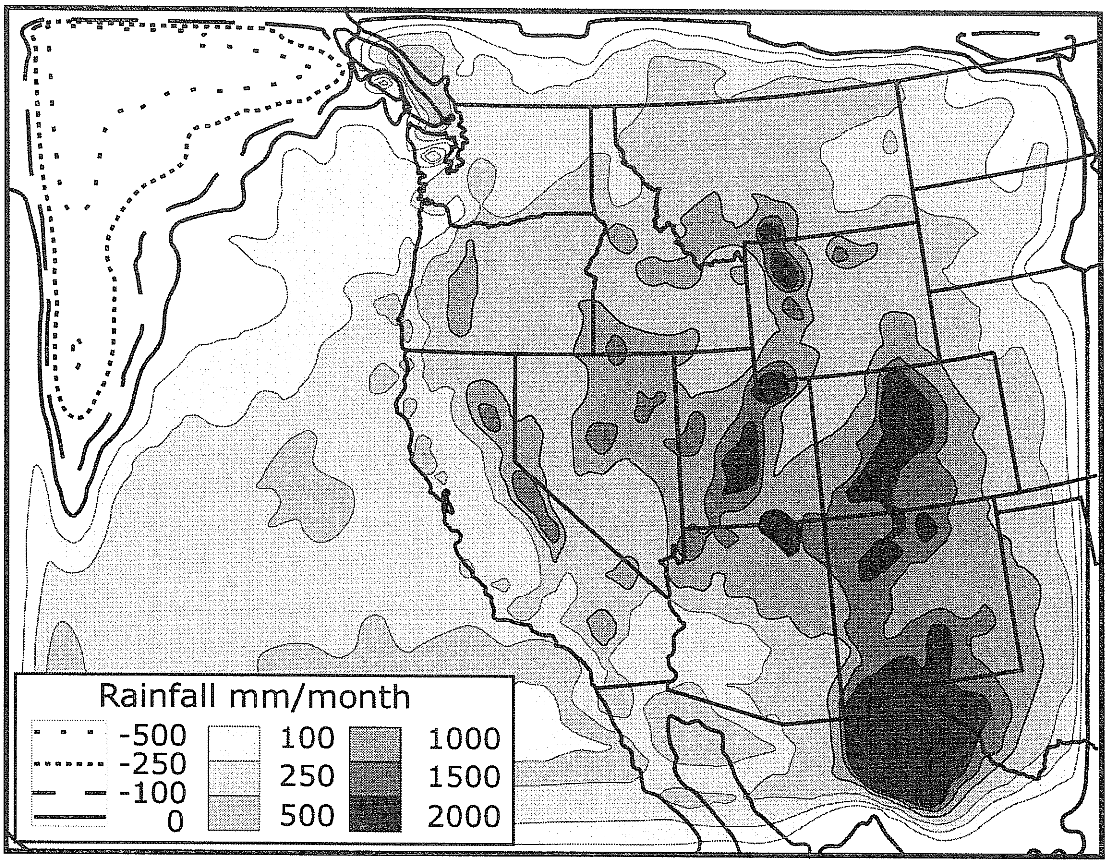

Figure 15. The Mean-Annual Precipitation Difference Between the Downscaled Control Simulation and the $2xCO_2$ Projection.

FUTURE RESEARCH

A more complete analysis using TOPMODEL for several coastal basins and the Sacramento Model for a large number of the CNRFC's operational basins are being planned when the most recent sub-daily GCM scenarios for present and $2xCO_2$ climate simulations become available. Results from this analysis will be provided after the level of confidence in the sensitivity response is improved. We recognize that there are uncertainties in GCM-simulated $2xCO_2$ scenarios. However, we have shown that we have the capability to downscale and analyze climate signals at a range of scales. Under a $2xCO_2$ atmospheric environment, a range of potential impacts to California water resources may occur. The consequences of these impacts may cause loss of life and large economic losses. Perhaps the solution would be to understand the likelihood of such impacts and to design an infrastructure that can handle a wide range of precipitation scenarios.

ACKNOWLEDGMENTS

This work is supported in part through funding provided by NASA/RESAC Grant NS-2791 for the USGCRP U.S. National Assessment of the Water Sector. Work for the Department of Energy is under Contract DE-AC03-76SF00098. We thank Daniel Cayan, Konstantine Georgakakos, and John Roads for useful discussions. We also thank Jung-Eun Lee for helping with data processing.

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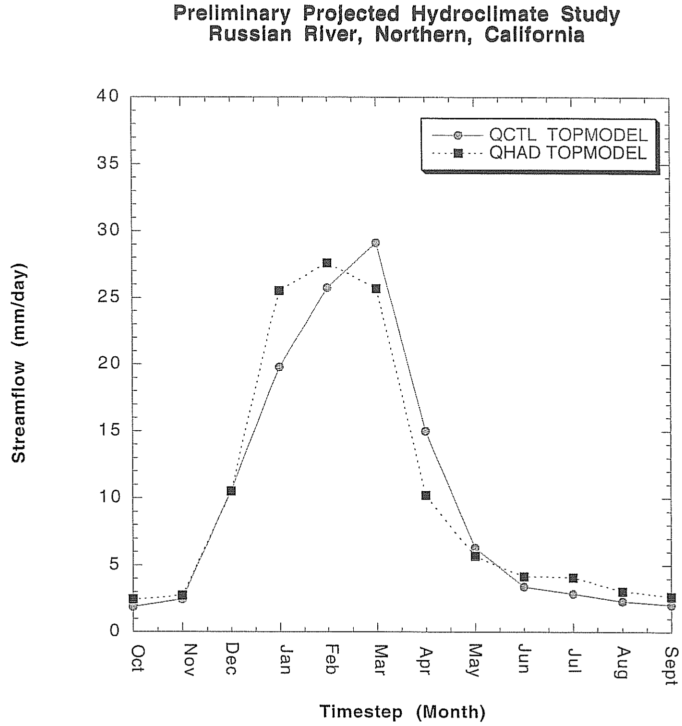

Figure 16. The Simulated Monthly Streamflow for the Control and $2xCO_2$ Climate.